

FURTHER ISOTOPIC STUDIES OF HEAVY NUCLEI IN THE 9/23/78 SOLAR FLARE

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ABSTRACT: We report further measurements and interpretation of He to Mg ($2 < Z < 12$) isotopes in the 9/23/78 solar flare. In particular, we have obtained a more accurate $^{22}\text{Ne}/^{20}\text{Ne}$ ratio by extending the energy interval for isotope analysis. We continue to find a significant difference between the $^{22}\text{Ne}/^{20}\text{Ne}$ ratio in this flare and that for the solar wind.

1. **Introduction:** Knowledge of the solar system isotope composition is essential to studies of the origin of the elements in stars, and studies of the solar system formation. Satellite-borne spectrometers which measure solar energetic particles (SEPs) now provide a new means of sampling directly the composition of solar material. Previously we have reported measurements of C, N, O, Ne, and Mg isotopes from the 9/23/78 solar flare observed by our instrument on ISEE-3^{1,2,3}. By extending the energy interval for isotope analysis, we have now improved our $^{22}\text{Ne}/^{20}\text{Ne}$ determination. We continue to find a significant difference between SEP and solar wind (SW) neon, which we compare to similar evidence from studies of SEPs implanted in lunar and meteoritic samples. New measurements of the composition and energy spectra of this event allow us to interpret our isotope measurements within a broader context of solar flare composition studies.

2. **Observations:** Caltech's Heavy Isotope Spectrometer Telescope (HIST) on ISEE-3 consists of a stack of silicon solid-state detectors, labeled M1, M2, and D1, through D9. For convenience, we label the "Range" of particles in HIST by the last detector triggered. In Fig. 1 we show mass histograms for 300 Ne events (see ref. 1 for data analysis details). Our earlier measurement¹ was based on Range 2 and Range 3 data. The bulk of the new data is at lower energy (Range 1), where the two position-sensitive detectors (M1 and M2) are used as ΔE devices. Although the Range 1 mass resolution (0.27 amu) is not expected to be as good as at higher energies (0.20 amu), there is a well-defined ^{22}Ne peak. Overall, we have more than doubled our sample of SEP Ne nuclei.

Fig. 2 shows the $^{22}\text{Ne}/^{20}\text{Ne}$ ratio in four energy intervals. Although it is possible that this ratio may vary with energy, we see no obvious trend. Similarly, we find no evidence for any significant variation in the $^{13}\text{C}/^{12}\text{C}$, $^{18}\text{O}/^{16}\text{O}$, $^{25}\text{Mg}/^{24}\text{Mg}$, or $^{26}\text{Mg}/^{24}\text{Mg}$ ratios with energy, nor do we find any significant time dependence for the isotopic composition during this solar event⁴. We therefore have no evidence to suggest that this event would have an anomalous isotopic composition.

Table 1 summarizes our results. Our improved $^{22}\text{Ne}/^{20}\text{Ne}$ measurement is somewhat smaller but consistent with our earlier value¹ of 0.13 (+0.04, -0.03). We have also improved our upper limit for $^{21}\text{Ne}/^{20}\text{Ne}$ and determined an upper limit for $^3\text{He}/^4\text{He}$. The C and Mg results in Table 1

were reported previously, while the 0 results have been revised slightly as a result of further analysis.

Because HIST selects events for analysis on the basis of their Range, the energy/nuc intervals for isotopes of a given element differ somewhat, with heavier isotopes having slightly lower energy/nuc thresholds for analysis. We corrected for this difference using the observed energy spectra, with the conventional assumption that the isotopic abundances are independent of energy/nuc, or equivalently, either velocity or momentum/nuc. An alternate possibility is that the abundances are independent of rigidity (or total momentum, assuming the isotopes of an element have the same charge). In this case the required correction is in the opposite sense and several times greater in magnitude, such that all values in Table 1 would be increased by an amount ranging from ~30% to ~70%⁴. This would imply that both ^{25}Mg and ^{26}Mg are significantly overabundant in this flare, by factors of ~50% and ~75% respectively. For ^{22}Ne there would be an overabundance of ~40% with respect to Cameron's value, or of ~140% with respect to the SW ^{22}Ne abundance. We conclude that the spectra of heavy elements in this event are better represented by a shape that is a function of energy/nuc or velocity.

In Fig. 3 we compare our results with tabulated solar system abundances⁵, SW measurements⁶, and other SEP

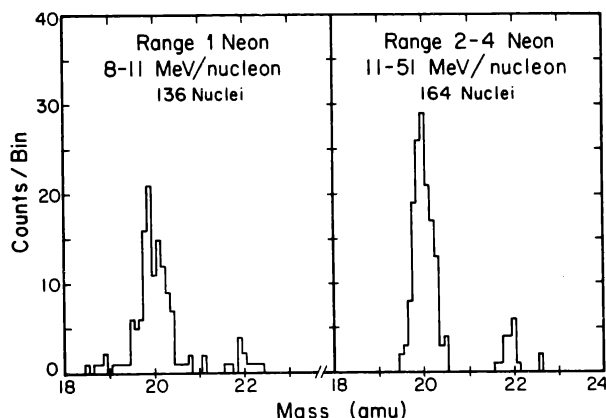


Fig. 1: Mass histograms of SEP Ne isotopes. The new data include the Range 1 data and 19 Range 2-4 events.

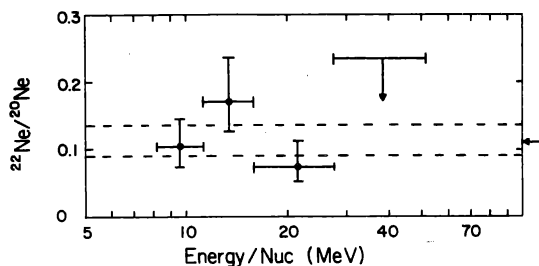


Fig. 2: $^{22}\text{Ne}/^{20}\text{Ne}$ vs. energy/nuc. The maximum likelihood value (arrow) and 86% confidence limits are indicated.

Table 1 - Isotope Ratios
9/23/78 Solar Flare

Isotope Ratio	Energy (MeV/nuc)	Observed Ratio ⁺	Solar System ⁵
$^3\text{He}/^4\text{He}$	5-32	< 0.0026	
$^{13}\text{C}/^{12}\text{C}$	6-39	$0.0095^{+.0042}_{-.0029}$	0.0112
$^{14}\text{C}/^{12}\text{C}$	6-39	< 0.0014	radioactive
$^{15}\text{N}/^{14}\text{N}$	9-42	$0.008^{+.010}_{-.005}$	0.0037
$^{17}\text{O}/^{16}\text{O}$	7-45	< 0.0021	0.00037
$^{18}\text{O}/^{16}\text{O}$	7-45	$0.0015^{+.0011}_{-.0007}$	0.00204
$^{21}\text{Ne}/^{20}\text{Ne}$	11-51	< 0.014	0.0030
$^{22}\text{Ne}/^{20}\text{Ne}$	8-51	$0.109^{+.026}_{-.019}$	0.122
$^{25}\text{Mg}/^{24}\text{Mg}$	12-36	$0.148^{+.043}_{-.025}$	0.129
$^{26}\text{Mg}/^{24}\text{Mg}$	12-36	$0.148^{+.046}_{-.026}$	0.142

⁺ 68% confidence intervals or 86% confidence limits

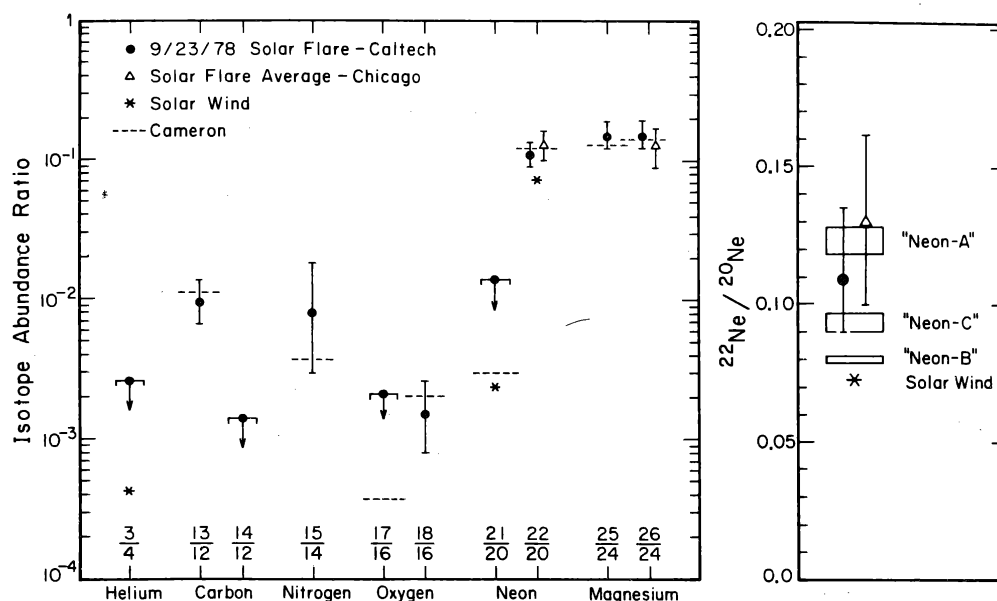


Fig. 3 (left): Comparison of isotopic abundances from SEPs (Table 1 and ref. 7,8), the SW⁶, and Cameron's solar system table⁵.

Fig. 4 (right): Comparison of solar system $^{22}\text{Ne}/^{20}\text{Ne}$ ratios. SEP measurements: ● Caltech; Δ Chicago⁷; Neon-A, -B, and -C are discussed in the text.

measurements^{7,8}. Note that in all cases our measured ratios are consistent with Cameron's tabulation. However, it should be pointed out that the Cameron abundances are based primarily on measurements of terrestrial and meteoritic samples, with little known about the extent to which they represent the composition of the Sun. This is especially true in the case of Ne, where, e.g., the recent Anders and Ebihara tabulation of solar system abundances⁹ uses the SW value ($^{22}\text{Ne}/^{20}\text{Ne} = .073$) rather than the meteoritic component neon-A ($^{22}\text{Ne}/^{20}\text{Ne} = 0.122$), which Cameron chooses.

3. Discussion: Fig. 4 shows selected solar system measurements of $^{22}\text{Ne}/^{20}\text{Ne}$ on an expanded scale. Included, in addition to the meteoritic components neon-A and neon-B¹⁰, is a third component, "neon-C", thought to represent SEP neon (≥ 1 MeV/nuc) directly implanted in lunar and meteoritic material. It is interesting that all of the attempts to measure this component (see summary in ref. 11) find a $^{22}\text{Ne}/^{20}\text{Ne}$ ratio greater than that of present day SW Ne, and with one possible exception¹², greater than that of neon-B, thought to represent implanted SW. In a recent review of these measurements¹¹ Black concludes that neon-C has $^{22}\text{Ne}/^{20}\text{Ne}$ ratio of 0.090 to 0.097. Note that neither of the two satellite measurements could be considered inconsistent with this range.

Thus, there are two independent approaches that find a difference

between SEP and SW neon. The question remains as to how the Sun can apparently emit two distinct isotopic components. We have previously considered the possibility of a linear, mass-dependent fractionation operating in either the solar flare acceleration or propagation processes, but found no evidence for such a pattern in our C, O, and Mg results³. Although relatively little is known about the SW isotopic composition, neither does it appear that the SW isotopes have been altered by a simple mass-dependent fractionation process.

There are also models that might produce selective enhancements. Fisk's model for "³He-rich" events¹³ can also enhance certain heavier elements. It is not clear, however, that it could produce isolated enhancements of individual heavy isotopes such as ²²Ne. Furthermore, we find neither a ³He enhancement nor an anomalous elemental composition in the 9/23/78 flare (our ³He/⁴He upper limit appears to be the lowest yet reported for a single solar event), suggesting that the conditions necessary for this model do not apply to this event. Mullen has proposed a pre-acceleration model that, on the average, would be expected to enhance the ²²Ne/²⁰Ne ratio more than other isotopic ratios¹⁴. A test of this model, not yet possible with present data, would be correlated enhancements of ²²Ne/²⁰Ne and ¹³C/¹²C. It appears that comprehensive measurements of a number of isotopic ratios in both the SW and in a number of SEP events may be required to relate the SW and SEP isotopic composition to that of the Sun.

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